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The step-like features on the I–V curves of the resonant tunneling diodes: current vortexes?

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Since the pioneering work of Tsu and Esaki [1], where the idea of the resonant tunneling diode was proposed, an enormous number of publications have been dedicated to its study. The range of the considered phenomena extends from the background physics to the design of sophisticated devices. Generally, transport through double barrier resonant tunneling structures (DBRTS) is considered as one-dimensional. Only recently few researchers begun to consider the lateral (in the plane of the barriers) current distribution [2, 3].

Here we present resonant tunneling current measurements in DBRTSs of various diameters, but with otherwisethe identical structure. I–V curves of samples with large diameters demonstrate step-like features in the negative differential conductance (NDC) region of the I–V curve. The features could be distinguished from the similar ones related to external circuit oscillations. It is shown that self-excitation of the current vortexes in the barrier region could be a possible reason for the observed step-like phenomena.

The samples were grown by MBE and are symmetric GaAs/$Al_{0.4}Ga_{0.6}As$ DBRTSs with 8.2 nm thick barriers and a quantum well of width 11.8 nm. The barriers are separated from the highly doped bulk contact regions by 30 nm thick undoped GaAs spacer layers. Samples of 5, 10, 20, 50 and 100 μm diameters were fabricated.

Fig. 1 shows I–V curves of a DBRTS with 10 μm diameter in various magnetic fields perpendicular to the current flow. The I–V curves coincide with that of a 5 μm diameter structure normalized to the mesa area. Magnetic field is applied to change the value of negative differential conductance σ which is the critical parameter in the theory of the external circuit oscillations. The variation of the I–V curves with magnetic field have been earlier studied in detail [4]. In that case it was discussed in terms of the Lorenz force with the help of a simple graphical model used for the description of the conservation laws describing the tunneling. It was shown that the in-plane magnetic field broadens the resonance: it moves to the right and decreases in amplitude. The same is observed in our structures.

All the I–V curves of the 10 μm and 5 μm structures are stable in the NDC region. There are no hysteresis or step-like features, which would appear if the external circuit oscillated [5]. It can be shown that the stability condition for the simple equivalent circuit

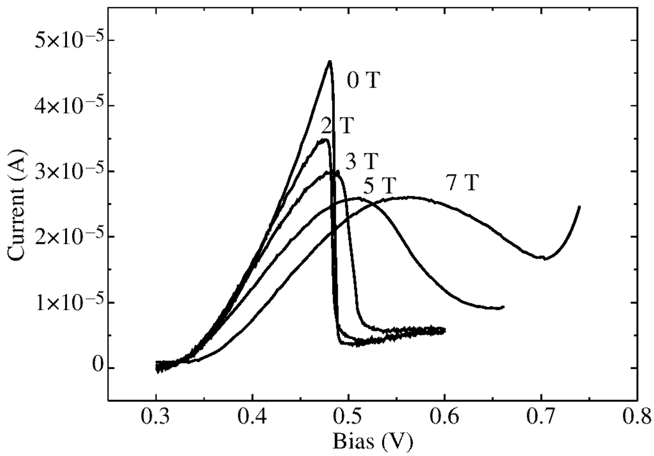

Fig. 1. Current-voltage characteristics of the DBRTS with 10 μm mesa diameter in the different magnetic fields perpendicular to the current flow. $T = 4.2$ K.

of a sample load resistor (R) in series with an inductor (L), and parallel to a sample capacitance (C) is

$$|\,\sigma\,| \;\leq\; \frac{R\,C}{L}, \tag{1}$$

The sample in this circuit is considered as a resistor with negative differential conductance σ.

It is clear from Fig. 1 that $|\,\sigma\,|$ decreases with magnetic field. We can consider the measured I–V curves of the 10 μm structure as the intrinsic ones of our DBRTS in so far as there are no oscillations in the NDC region. With the increase of the magnetic field from 0 to 7T, $|\,\sigma\,|$ decreases 100 times. This means that the stability condition should be fulfilled for all the samples with diameters up to 100 μm in magnetic field B=7T in the same experimental environment. This may not be true for smaller magnetic fields and below we focus on the data when the stability condition is satisfied.

Fig. 2 shows I–V curves measured on 20, 50 and 100 μm diameter samples in a magnetic field of $B = 7$ T. The currents are normalized to 10 μm mesa diameter. All the curves were measured with the same external circuit. Step-like features in the NDC region appear and the number of steps is roughly proportional to the mesa diameter. Using a standard oscilloscope we did not observe any oscillations in the NDC regions of the I–V curves shown in Fig. 2.

To emphasize the above observations Fig. 3 shows the differential conductance of the 10 μm sample in $B = 2$ T, and that if the 20 μm sample in $B = 7$ T. The 20 μm sample has one step in the NDC region when $|\,\sigma\,|$ is much less then the maximum negative differential conductance of the 10 μm structure.

We argue that one of the possible reasons for appearance of the observed steps is the following. Let's choose the the growth direction as the z-axis, and the y-axes along the magnetic field B. It is natural to suppose that the local intrinsic I–V curve has a form analogous to that shown in the Fig. 1. Fluctuations of the charges in the semiconductor regions can build up under certain conditions due to the fact that σ is negative. In more formal language that means that the so-called junction plasmons [6, 7] are unstable. In the vicinity of an arbitrary point on the I–V curve (V_0, j_0) the build up of the instability

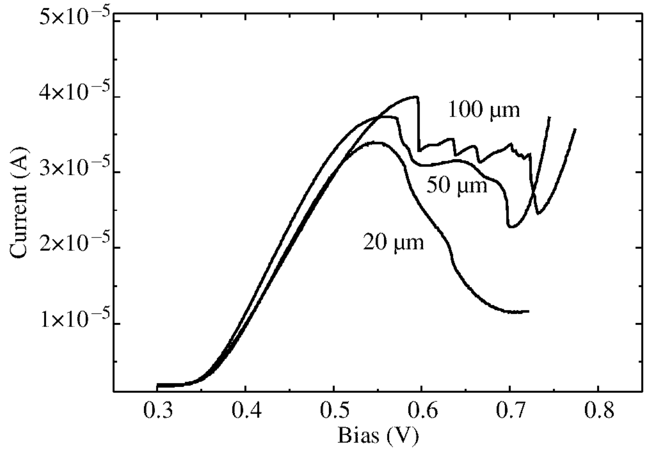

Fig. 2. Current–voltage characteristics measured on 20, 50 and 100 μm samples in magnetic field of $B = 7$ T perpendicular to the current flow. The currents are normalized to 10 μm mesa diameter. $T = 4.2$ K.

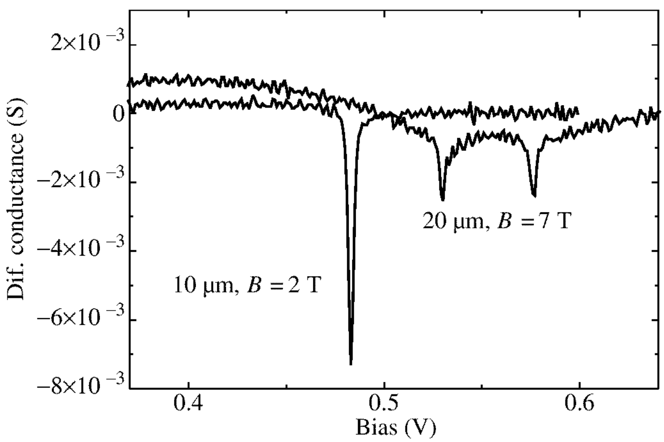

Fig. 3. Differential conductance of the 10 μm sample in the field of $B = 2$ T, and of the 20 μm sample in the field of $B = 7$ T. $T = 4.2$ K.

can lead to a current vortex. The fact that the current lines are closed means that the current fluctuations in the x-direction (δj_x) in the upper n-GaAs layer are closed in the z-direction through the fluctuation of the tunnel current (δj_z). The fluctuations $\delta j_z = \sigma \delta V$ and $\delta j_x = \sigma_{xx} \delta E_x$ are connected with each other by the continuity equation: $\delta j_x + \delta j_z = 0$. Taking into account that the fluctuation of the lateral electric field is $\delta E_x \approx \delta V / L_x$, one can obtain an assessment of the lateral size of the vortex:

$$L_x(B) \approx \frac{\sigma_{xx}(B)}{\sigma(B)}. \tag{2}$$

In our samples we estimate L_x is of the order of 100 μm in $B = 7$ T. If the diameter of the DBRTS is less than L_x the vortexes cannot appear and there are no steps in the I–V

curve. If the diameter increases or $L_x(B)$ diminishes, at first one vortex appears, then two vortexes, etc. Each one of them is accompanied by a step-like feature on the I–V curve.

Thus we have found the step-like features in the I–V curves of double-barrier resonant tunneling structures. These cannot readily be explained in terms of external circuit oscillations. A theoretical model is proposed that the appearance of the step-like features in the negative conductance region of the I–V characteristics is due to the self-excitation of current vortexes in the barrier region of the DBRTS.

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